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MULTIFAULT ISOLATION IN LINEAR NETWORKS BY THE METHOD OF JOINT SIGNATURE

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THESIS

Multifault Isolation in Linear Networks
by the Method of Joint Signature

by

Gary Lamour Long

Thesis Advisor: S. G. Chan

December 1971

Approved for public release; distribution unlimited.

Multifault Isolation in Linear Networks by the Method of Joint Signature

by

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B.S., Naval Postgraduate School, 1970

Submitted in partial fulfillment of the requirements for the degree of

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December 1971

ABSTRACT

A study was made to isolate one and two component faults in simple linear networks by the method of joint signature of order two whereby two measurements of a failed network are coded to all possible combinations of two component values which will produce that fault with all other elements at nominal values. Two additional measurements were obtained, a new joint signature of order two generated, and the faulty component set was selected as the fault pair with the same values at both joint signatures. The method involves numerous solutions of sets of nonlinear equations. By assuming many values of a failed network function the equations were presolved on a one time only basis for a network. One and two component faults were simulated in two simple low pass filter networks. The highest success rate in isolating faults was approximately 80%.

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I. INTRODUCTION

A. HISTORICAL BACKGROUND

1. Single Fault Isolation

Although there has long been an interest in fault isolation procedures, efforts in devising fault detection techniques have generally lagged behind other aspects of network theory. With the increasing sophistication of modern electronic systems came the progressively more complex trouble shooting procedures which are embodied in the automatic and semi-automatic test equipments, basically using one electronic system to check the performance of another. Although effective, these methods have proved to be expensive both monetarily and in the consumption of engineering expertise since generally test equipment has been designed to check only a specific system or specific type of network. It is against this background that some recent developments in fault isolation practices have attracted new attention, not so much because of the encouraging results obtained from experimental application as from the promise of a general fault isolation procedure applicable to a large class of electrical networks. The techniques developed thus far are still restrictive, applying only to single faults in linear networks, but form the nucleus of an emerging field of fault isolation theory.

a. The Proposal of Fault Signatures

Seshu and Waxman [1] were the first to propose a system of fault isolation by matching each element in a linear network with the signature of faults that the particular element could produce. Then by taking several measurements of a failed network and determining the fault signature, one could presumably detect the faulty element by matching

fault signatures. Seshu and Waxman proposed using test frequencies below the lowest nonzero break frequency, at least one above the highest finite break frequency and several test frequencies near complex poles and zeros. Their fault signatures were based solely upon the magnitude of the network function. In an analysis of an eight element one transistor network, where the transistor was replaced by the hybrid parameter model, Seshu and Waxman found that 41 of 62 computed fault signatures identified the faulty component uniquely while 15 others isolated the fault to two components. No experimental results were reported.

b. Experimental Results Using Fault Signatures

Stahl, Maenpaa and Stehman [2] have reportedly been 78% to 98% suscessful in isolating single element faults to a single component in linear networks of 8 to 15 components. Utilizing a computer program for fault diagnosis as proposed by Seshu and Waxman, they generated signatures and test frequencies for single element variations. The number of test frequencies used was three plus one for each complex breakpoint frequency between extreme critical frequencies. The network model employed was a two-port and the input impedance and voltage transfer ratio were the measured network functions. It is perhaps of importance to note that the approach of the two mentioned groups of authors does not make direct use of the bilinear nature of a linear network function F(s) to variations in a circuit element's value as presented by DeClaris [3]. By utilizing the bilinear property, which of course requires phase measurements, one can ascertain approximate values of a faulty component which can be used to choose between two or more possible faulty components.

2. Multiple Faults

Phung and Chan [4] have proposed an extension to fault isolation theory to include multiple faults in linear networks. The concept of a joint signature of order K was introduced whereby those combinations of K single element faults, i.e., K faulty elements, causing a network function F(s) to lie within some small area of the F(s) plane were coded with a signature. Then, by taking measurements of F(s), one could search the sets of elements with joint signature corresponding to the measured value of F(s) to determine the faulty set.

B. GOAL OF FAULT ISOLATION TECHNIQUES

The ultimate goal of fault isolation theory is to produce procedures whereby any number of faults in any type of network can be isolated with a minimum number of measurements and requiring little knowledge of circuit theory on the part of the individual isolating the faults. This means that a technician, by taking a few simple measurements, should be able to pinpoint faulty network components in all types of networks. In addition, the procedure should be capable of being automated.

II. THE PROBLEM

A. APPROACH

In this paper the concept of joint signature of order K, presented by Phung and Chan, is extended, by heuristic mathematical concepts, to include approximations of faulty component values and to include a mathematical basis for determing the number of test measurements required. Two simple example problems were treated by generating fault signatures and corresponding network function values via digital computer applications.

B. MULTIFAULT ISOLATION BY JOINT SIGNATURE

A method will be described whereby one can determine the approximate values of faulty network parameters. The term parameters is used to include all variables, except frequency or time, which appear in the mathematical description of the network function to describe the network input response relationship. By comparing determined values to nominal falues, faults may be isolated to any number of parameters. Since approximate parameter values are to be determined only one network function need be measured. In concept the network may either be linear or nonlinear requiring only that the output response to a given input be describable in either the time or frequency domain by a set of simultaneous nonlinear equations in which the unknowns are a set of network parameters. However, the following discussion assumes a linear network and further assumes that the network parameters are frequency independent such as would be the case if the network function were expressed in terms of elements once the complex frequency s was treated as a known constant.

Consider a network function $T(s,\underline{x})$ which is a ratio of polynomials in s and the vector $\underline{x}$ of all network parameters. Assume that there are N such parameters. Then, knowing that the network is faulty, N measurements are required to obtain N equations to solve for the network parameters. There are N unknowns. However, by assuming that there are a maximum of K faulty elements, the number of unknowns may be reduced.

The joint signature of order K is now defined as any possible combination of K parameter values which, with the remaining N-K parameters at nominal values, will cause the network function to have K specific values. In regard to a linear network, network function is now defined as a real equation such as $|T(s,\underline{x})| = 1.0$, $\angle T(s,\underline{x}) = 90°$ or Imaginary part of $\{T(s,\underline{x})\} = 0.6$. In general there are $\binom{N}{K} = \frac{N!}{K!\,(N-K)!}$ such sets of K element values hereafter referred to as possible fault sets. These $\binom{N}{K}$ possible fault sets are all combinations of K element values, N-K remaining at nominal, which satisfy a set of K nonlinear equations. Note that not all members of a possible fault set need have a value different from nominal. Maintaining the assumption of a maximum of K faults let one take K measurements, determine the joint signatures of order K corresponding to the measured values and obtain the possible fault sets. By eliminating one previous measurement (equation) and obtaining a new one, a new set of possible fault sets is obtained with new joint signatures of order K. Borrowing from the theory of linear algebra, if there are K unknowns or K faults, an excess equation exists and th overall set of K+1 equations will be consistent for only one possible fault set (assuming linearity), the actual set of K faulty elements. The actual fault set could be determined by comparing the possible fault sets from the first K equations with those from the second K equations and selecting the possible fault set

common to both sets of equations. Two theoretical problems exist. First, the equations are nonlinear so that there may be more than one common possible fault set with two distinct joint signatures of order K. To reduce resulting ambiguities additional excess equations may be obtained. In fact, the second set of K equations may be entirely different from the first. The second problem, the assumption of a maximum of K faults, is more important. If the assumption is not true the procedure will fail but its failure may be detected by the troubleshooting technician. If there is no common possible fault set corresponding to the joint signatures, one can see that there are actually more than K network faults. Since the network equations are nonlinear, a second excess equation is required to reduce ambiguities if more than K faults are to be detected. Thus the choice of K is critical, a compromise between the complexity of calculations and the depth of fault isolation desired. The procedure for multifault isolation is now summarized below.

Step 1. Choose the maximum number of faults K to be considered.

Step 2. Take K network measurements to obtain K equations.

Step 3. Solve the K equations for the $\binom{N}{K}$ possible fault sets associated with the joint signature of order K.

Step 4. Eliminate one or more equations and take new measurements to obtain a new set of K equations.

Step 5. Solve the new equations for $\binom{N}{K}$ possible fault sets.

Step 6. Choose the common possible fault set from steps 3 and 5 as the fault set.

Step 7. If one desires to detect the presence of more than K faults, repeat the procedure. Compare the two fault sets from Step 6. If the two fault sets are different, there are more than K network faults.

C. PARAMETER PRESOLUTIONS

None of the proceding discussion is of importance to the network analyst diagnosing faults who does not have access to a digital computer unless, in some manner, the sets of simultaneous non-linear equations can be presolved. This can be accomplished by taking typical output values of a failed network and using these typical values as approximations to the actual measured values.

As an example consider a linear network function $T(s,\underline{x})$. Suppose $|T_o(s,\underline{x})|$ is the nominal output magnitude for a specified input and $\angle T_o(s,\underline{x})$ is the nominal phase relationship. By taking areas of interest about the nominal values and dividing this region into cells, one can presolve the equations based on the values $|T(s,\underline{x})|$ and $\angle T(s,\underline{x})$ at the centers of these cells. Then, when actual circuit measurements are taken and plotted into a particular set of cells, these cells will be coded to

a set of faulty parameters whose value has previously been determined by the procedures established in the preceding section. The complex calculations need be done only once for any network. Further, calculations may be performed on an impedance and frequency normalized model and the parameter values can merely be unscaled to apply to any original network.

III. EXPERIMENTAL PROCEDURE

A. PROBLEM ONE

1. Network

The network chosen for example one was a third order low pass Chebyshev filter with cut off frequency at 2500 radians per second and source resistance as shown in Figure 1. The network function used was the voltage transfer function with components as the parameters.

2. Number of Faults and Test Frequencies

Only one and two component faults were considered here. Test frequencies were selected at either side of the cut off frequency at 1500 and 3500 radians per second. The cut off frequency of 2500 radians per second was also used. The codes A, B, and C were used to identify the three frequencies 1500, 2500, and 3500, respectively. After it was determined that the use of a third test frequency did not appreciably affect results, the test frequency 2500 was discarded.

3. Problem Limitations

In order to limit the scope of the problem only variations in the real part of $T(s,\underline{x})$ of ±22.5% or less of the magnitude of the nominal $T(s,\underline{x})$ were considered at each test frequency. Simulated failed network function values which fell outside this region were discarded. The imaginary part was similarly restricted. The cell size chosen in the complex $T(s,\underline{x})$ plane was d units wide (real part) and d units high (imaginary part) where $d = 0.05 \cdot |T_o(s,\underline{x})|$ at the frequency of concern. The real and imaginary parts of $T(s,\underline{x})$ were considered, rather than magnitude and phase, to ease bookkeeping problems. The value of d was

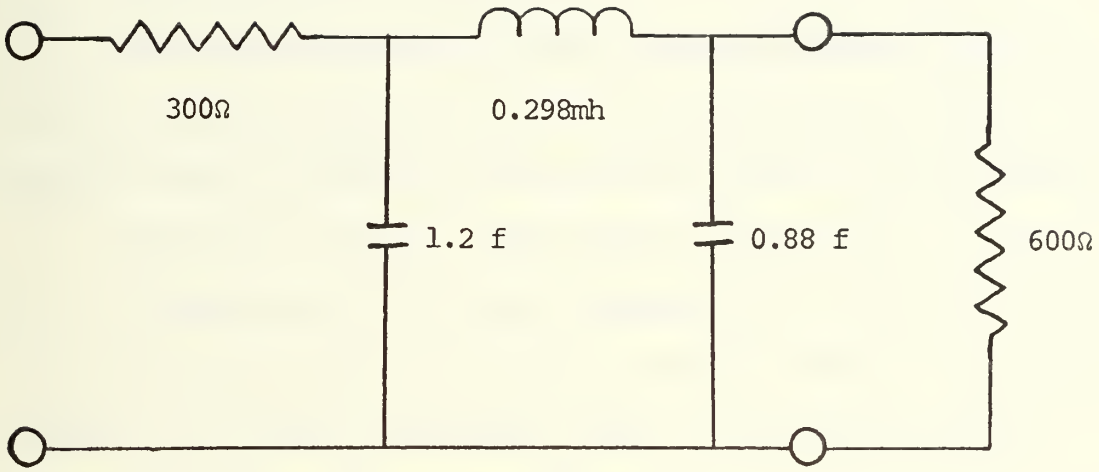

FIGURE ONE

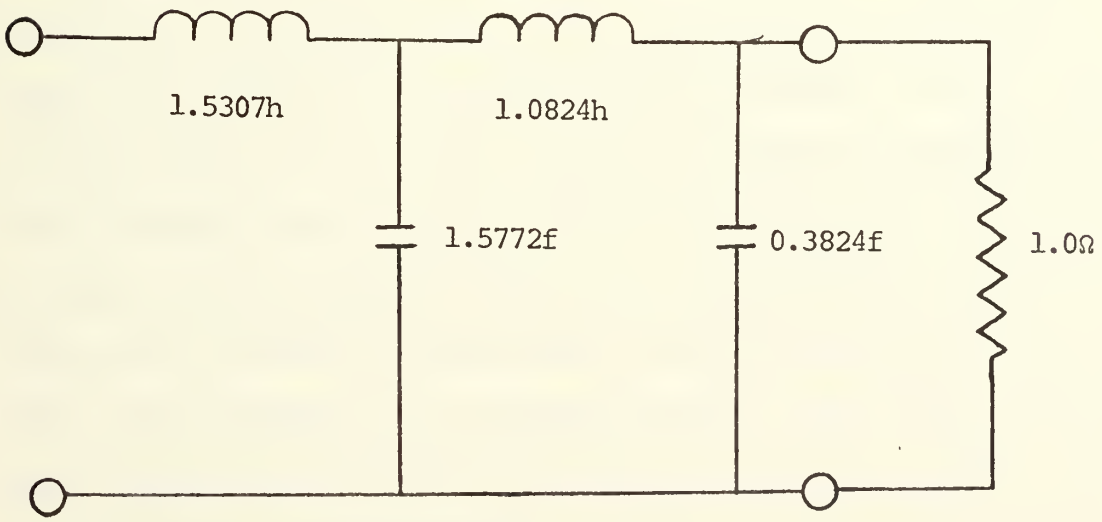

FIGURE TWO

selected as a reasonably small cell size compatible with approximation and yet within the accuracy of standard measuring equipment. The cells were then numbered as in Figure 3 where A is coded to s = j1500.

4. Generating Joint Signatures

The joint signatures of order two were generated by solving the two nonlinear equations below for all ten possible combinations of the five network elements and for each cell center at each frequency.

Real part of $T(s,\underline{x})$ = Real part of center of cell ij.

Imaginary part of $T(s,\underline{x})$ = Imaginary part of center of cell ij. The equations were solved utilizing an earlier version of the computer program at the end of this thesis with a 73% success rate when an accuracy of 0.1% was required on $|T(s,\underline{x})|$.

5. Fault Definition and Fault Set Selection

Numerous one and two element variations were simulated and values of $T(s,\underline{x})$ computed. These values of $T(s,\underline{x})$ were then plotted at both test frequencies. If at either test frequency the value of $T(s,\underline{x})$ plotted fell outside the cell whose center was the nominal value of $T(s,\underline{x})$ then a fault was considered to exist. For example, a value of $T(s,\underline{x})$ at s = j1500 might lie in cell 37A while at s = j3500 $T(s,\underline{x})$ might lie in cell 64C for the same element variations. Then all ten possible fault sets with joint signature of order two corresponding to cell 37A were compared to the possible fault sets with joint signature of order two corresponding to cell 64C. The actual fault set was selected by choosing the element pair with the smallest percentage variation (from frequency A to C) from the nominal value, based on the element from each pair which had the largest percentage variation. Once the fault pair was determined the fault set was obtained by averaging

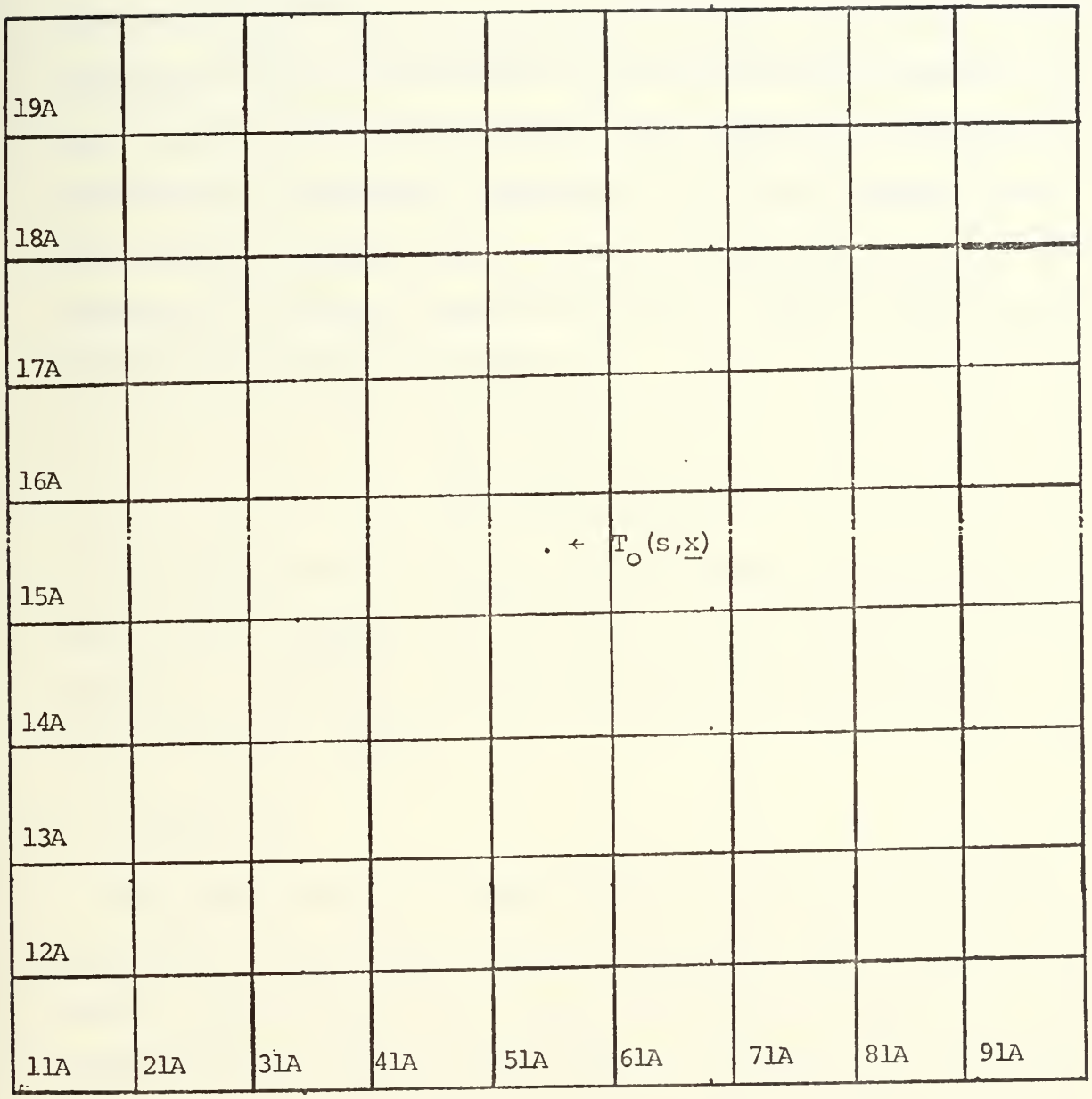

FIGURE THREE

the values of the fault pair at the two frequencies. Consider the element pair x_i and x_j. Let x_{iA}, x_{jA} be the possible fault set of these two elements at frequency A, etc. Then for each of the ten element pairs the percentage variation from the nominal value for each element was computed as $\left|\frac{x_{iA} - x_{iC}}{x_{io}}\right| \times 100$ where x_{io} is the nominal value of x_i. Of each element pair only the element with the largest percentage variation (the most deviant element) was considered. Then among the ten element pairs the 10 values of percentage variation for the 10 most deviant elements were compared. The fault pair was selected as the pair whose most deviant element had the smallest percentage variation. After the fault pair was determined the fault set was taken as:

$$x_{iF} = (x_{iA} + x_{iC})/2$$

$$x_{jF} = (x_{jA} + x_{jC})/2.$$

It can be seen that this decision criteria depends on the logarithmic sensitivities, $\frac{\partial T(s,\underline{x})}{\partial \ln x_i}$, being of the same order of magnitude for all elements i. Otherwise, fault selection favors the most sensitive (logarithmically) elements.

B. PROBLEM TWO

The network chosen for problem two was a normalized fourth order butterworth low pass filter as shown in Figure 2. Test frequencies used were $s_A = j0.5$ and $s_B = j1.2$. Again only one and two element faults were considered and a 5% cell size was used. The limitation of ±22.5% variation in $T(s,\underline{x})$ was retained. The program used to generate cells and joint signatures was that at the end of this thesis. The programs were run on the Naval Postgraduate School's IBM 360/67. The execution times were approximately 13 minutes for each test frequency. Since there were

10 element pairs and 81 cells at each frequency, this is about one second per solution of a set of equations. In the execution phase the program requires 66,000 bits of storage. The program is not presented as an example of efficient programming nor are any claims made as to the class of problems it will handle. However, in problem two the program was 94% successful in obtaining a solution to the sets of equations. Again required accuracy was 0.1% of $|T(s,\underline{x})|$. The fault set selection criteria were as in problem one. Attempts were made to normalize x $\Delta x_i = x_{iA} - x_{iB}$ by multiplying by the absolute value of the nonlogarithmic sensitivity, $|\frac{\partial T(s,\underline{x})}{\partial x_i}|$. If one lets $dT(s,\underline{x}) = \frac{\partial T(s,\underline{x})}{\partial x_i} \cdot \Delta x_i$ and selects the fault pair on the vasis of the smallest value $|dT(s,\underline{x})|$, this is seen to be a first order correction. The procedure heavily favored the least sensitive elements and was abandoned in favor of the previous selection criteria.

IV. DATA

A. PROBLEM ONE

1. Summary of Data for One and Two Component Faults

In order to minimize misrepresentation the data is presented in tabular form. Only element values other than those nominal ones have been listed and so care must be exercised in interpretation since the method of joint signature of order K always produces K "faulty" parameters even though some parameters may not be faulty at all. For instance, test No. 110 lists $x_2 = 1.59$, $x_5 = 591$ as a fault set while only x_2 is an actual faulty element. Inspection reveals that the nominal value of $x_5 = 600$ ohms and so the fault value is less than 1% from nominal or no fault at all. In an effort to simplify interpretation, results have been labeled as successful, partially successful and failure. The only true measure of success must be the return of the network to a non-faulty condition when the indicated faulty elements are replaced by components at nominal value. Accordingly, success has been defined as the case where the indicated fault pair agreed with the actual fault pair regardless of values except for very small differences previously discussed. Partial success means that a determined fault set agreed with the actual fault set as far as the element with largest percent variation was concerned. Program failure indicates that the computer program did not solve for the joint signature of order K of the actual fault set at one or both test frequencies. In these cases the selection of a fault set could not possibly have been correct since needed information was missing.

A summary of the results for problem one are listed below.

Number of Tests	Successful	Partially Successful	Program Failures
44	22	7	6

Number of Failures
15

2. Table of Data for One and Two Component Faults

TEST #	CELLS	DETERMINED FAULT SET*	ACTUAL FAULT SET*	SUCCESS	PROGRAM FAILURE
2	73A/38C	X3 = 293 X5 = 795	X5 = 800	YES	NO
8	63A/48C	X2 = 1.26 X5 = 763	X4 = 0.90 X5 = 750	YES	NO
9	45A/76C	X4 = 0.97 X5 = 574	X4 = 0.98	YES	NO
10	54A/77C	X4 = 0.96 X5 = 642	X4 = 0.98 X5 = 650	YES	NO
23	45A/66C	X1 = 309 X4 = .95	X4 = 0.95	YES	NO
45	65A/34C	X4 = 0.80 X5 = 633	X3 = 280	NO	NO
46	76A/13C	X3 = 257 X5 = 594	X3 = 260	YES	NO
50	45A/76C	X4 = 0.98 X5 = 574	X3 = 325	NO	NO
58	25A/96C	X3 = 352 X5 = 588	X3 = 352	YES	NO
59	46A/64C	X3 = 302 X5 = 532	X5 = 540	YES	NO
70	35A/85C	X3 = 358 X4 = 0.78	X3 = 325 X5 = 575	PARTIAL	NO
75	31A/98C	X3 = 334 X5 = 708	X3 = 360 X5 = 800	YES	NO
76	83A/17C	X4 = 0.79 X5 = 812	X3 = 280 X5 = 800	PARTIAL	NO
77	74A/26C	X3 = 279 X5 = 710	X3 = 285 X5 = 700	YES	NO
78	33A/97C	X1 = 269 X4 = 1.15	X3 = 352 X5 = 700	NO	NO
79	45A/74C	X3 = 344 X4 = 0.77	X3 = 352 X4 = 0.75	YES	NO

*X1 and X5 are in ohms, X3 in millihenries, X2 and X4 in microfarads.

TEST #	CELLS	DETERMINED FAULT SET	ACTUAL FAULT SET	SUCCESS	PROGRAM FAILURE
81	55A/56C	X2 = 1.22 X5 = 618	X3 = 280 X4 = 0.95	NO	NO
90	44A/78C	X2 = 1.47 X5 = 660	X2 = 240 X4 = 1.35	NO	YES
92	55A/77C	X1 = 316 X4 = 0.91	X3 = 280 X4 = 1.05	NO	NO
97	55A/67C	X4 = 0.92 X5 = 630	X3 = 250 X4 = 1.20	NO	NO
102	65A/31C	X1 = 290 X3 = 301	X2 = 0.95	NO	NO
110	35A/98C	X2 = 1.59 X5 = 591	X2 = 1.60	YES	NO
118	35A/88C	X2 = 1.54 X5 = 606	X2 = 1.54 X5 = 615	YES	NO
119	56A/64C	X3 = 292 X5 = 539	X5 = 560	YES	NO
121	74A/13C	X2 = 0.96 X5 = 707	X2 = 0.95 X5 = 680	YES	NO
125	45A/67C	X2 = 1.36 X5 = 624	X2 = 1.35 X5 = 625	YES	NO
127	56A/63C	X2 = 1.12 X5 = 528	X2 = 1.15 X5 = 525	YES	NO
131	37A/94C	X3 = 320 X5 = 477	X2 = 1.33 X5 = 450	PARTIAL	NO
132	36A/87C	X1 = 361 X3 = 318	X2 = 1.15 X5 = 525	NO	NO
137	47A/51C	X3 = 275 X5 = 465	X2 = 1.90 X4 = 0.50	NO	YES
139	45A/66C	X3 = 314 X5 = 595	X2 = 1.50 X4 = 0.78	NO	NO
141	34A/98C	X2 = 1.64 X5 = 631	X2 = 1.48 X4 = 0.95	PARTIAL	NO
142	44A/87C	X4 = 1.03 X5 = 611	X2 = 1.33 X4 = 0.98	NO	YES

TEST #	CELLS	DETERMINED FAULT SET	ACTUAL FAULT SET	SUCCESS	PROGRAM FAILURE
144	45A/76C	X4 = 0.97 X5 = 574	X2 = 1.60 X4 = 0.76	NO	NO
146	44A/87C	X4 = 1.02 X5 = 611	X2 = 1.15 X4 = 1.05	NO	YES
156	46A/69C	X2 = 1.33 X5 = 637	X2 = 1.90 X3 = 240	NO	YES
166	45A/65C	X3 = 311 X5 = 584	X2 = 1.15 X3 = 316	YES	NO
176	56A/66C	X1 = 335 X3 = 334	X1 = 344	YES	NO
180	64A/44C	X1 = 266 X3 = 294	X1 = 265	YES	NO
196	81A/27C	X2 = 1.16 X5 = 900	X1 = 265 X5 = 816	PARTIAL	NO
198	72A/13C	X2 = 1.08 X5 = 789	X1 = 220 X5 = 680	NO	YES
199	55A/56C	X1 = 307 X5 = 619	X1 = 318 X5 = 625	YES	NO
200	64A/32C	X1 = 257 X2 = 1.11	X1 = 235 X5 = 575	PARTIAL	YES
205	55A/69C	X2 = 1.30 X5 = 700	X1 = 360 X5 = 750	PARTIAL	NO

B. PROBLEM TWO

1. Summary of Data

The conditions for success and failure were as in problem one. Since the program successfully solved for 94% of the joint signatures, no program failures have been indicated. Instead, those few tests which involved program failures were completely ignored. A summary of the results of problem two are given below.

Number of Tests	Successful	Partially Successful	Failures
74	55	9	10

2. Table of Data

TEST#	CELLS	DETERMINED FAULT SET*	ACTUAL FAULT SET*	SUCCESS
3	54A/45B	X1 = 1.54 X5 = 1.06	X5 = 1.05	YES
5	56A/65B	X1 = 1.52 X5 = 0.94	X5 = 0.95	YES
6	67A/37B	X1 = 1.34 X5 = 0.87	X1 = 1.33 X5 = 0.85	YES
7	48A/75B	X4 = 0.35 X5 = 0.84	X5 = 0.85	PARTIAL
8	38A/95B	X2 = 1.68 X5 = 0.84	X2 = 1.63 X5 = 0.80	YES
9	49A/85B	X1 = 1.50 X5 = 0.80	X5 = 0.80	YES
12	62A/34B	X1 = 1.56 X5 = 1.20	X5 = 1.15	YES
13	52A/54B	X1 = 1.62 X5 = 1.16	X1 = 1.63 X5 = 1.15	YES
14	71A/34B	X1 = 1.54 X5 = 1.24	X5 = 1.25	YES
15	51A/53B	X1 = 1.68 X5 = 1.26	X1 = 1.68 X5 = 1.25	YES
20	53A/45B	X1 = 1.56 X5 = 1.08	X5 = 1.10	YES
21	34A/83B	X1 = 1.46 X5 = 1.18	X1 = 1.78 X5 = 1.10	YES
24	72A/34B	X4 = 0.36 X5 = 1.20	X5 = 1.20	PARTIAL
25	82A/25B	X1 = 1.88 X5 = 1.14	X1 = 1.47 X5 = 1.20	YES
35	49A/85B	X1 = 1.50 X5 = 0.80	X4 = 0.35 X5 = 0.80	PARTIAL

*X1 and X3 are in henries, X2 and X4 in farads, X5 in ohms.

TEST #	CELLS	DETERMINED FAULT SET	ACTUAL FAULT SET	SUCCESS
38	54A/46B	X1 = 1.43 X2 = 1.67	X4 = 0.46 X5 = 1.05	NO
39	52A/37B	X4 = 0.51 X5 = 1.12	X4 = 0.51 X5 = 1.15	YES
36	67A/63B	X4 = 0.20 X5 = 0.95	X4 = 0.19 X5 = 0.95	YES
67	47A/95B	X2 = 1.64 X5 = 0.88	X2 = 1.68 X5 = 0.85	YES
70	55A/56B	X1 = 1.47 X2 = 1.62	X4 = 0.43	NO
71	45A/65B	X1 = 1.60 X4 = 0.42	X1 = 1.59 X4 = 0.43	YES
73	56A/47B	X2 = 1.48 X3 = 1.20	X2 = 1.48 X3 = 1.18	YES
74	57A/17B	X1 = 1.38 X5 = 0.91	X2 = 1.38 X3 = 1.19	NO
78	56A/48B	X2 = 1.46 X3 = 1.24	X2 = 1.44 X3 = 1.23	YES
79	54A/54B	X1 = 1.59 X5 = 1.10	X2 = 1.63 X3 = 1.03	NO
82	35A/74B	X1 = 1.68 X2 = 1.60	X1 = 1.69	YES
85	55A/45B	X1 = 1.50 X3 = 1.07	X1 = 1.50	YES
87	45A/74B	X1 = 1.65 X5 = 1.01	X1 = 1.67	YES
88	35A/94B	X1 = 1.66 X2 = 1.67	X1 = 1.67 X2 = 1.68	YES
89	55A/65B	X2 = 1.60 X3 = 1.08	X1 = 1.56	NO
91	65A/45B	X1 = 1.46 X4 = 0.35	X1 = 1.48	PARTIAL

TEST #	CELLS	DETERMINED FAULT SET	ACTUAL FAULT SET	SUCCESS
94	55A/77B	X3 = 1.16 X5 = 1.05	X3 = 1.18	YES
95	65A/36B	X1 = 1.42 X5 = 0.99	X1 = 1.42	YES
96	66A/89B	X1 = 1.38 X3 = 1.35	X1 = 1.42 X3 = 1.28	YES
97	75A/16B	X1 = 1.38 X2 = 1.55	X1 = 1.36	YES
103	26A/93B	X1 = 1.83 X5 = 1.00	X1 = 1.85	YES
105	45A/64B	X1 = 1.63 X2 = 1.57	X1 = 1.60	YES
107	45A/74B	X1 = 1.65 X5 = 1.01	X1 = 1.63	YES
109	66A/63B	X4 = 0.23 X5 = 0.98	X4 = 0.26	YES
111	65A/31B	X3 = 0.95 X4 = 0.30	X3 = 0.94 X4 = 0.34	YES
114	54A/23B	X2 = 1.58 X3 = 0.96	X3 = 0.96 X4 = 0.46	PARTIAL
117	34A/78B	X2 = 1.66 X4 = 0.56	X2 = 1.68 X4 = 0.57	YES
128	56A/96B	X3 = 1.29 X4 = 0.32	X3 = 1.24 X4 = 0.30	YES
129	56A/76B	X3 = 1.29 X4 = 0.32	X3 = 1.18 X4 = 0.33	YES
130	55A/68B	X1 = 1.48 X3 = 1.14	X3 = 1.13	YES
132*	66A/63B	X4 = 0.23 X5 = 0.98	X4 = 0.25	YES

*This fault is almost identical to that of Test #109.

TEST #	CELLS	DETERMINED FAULT SET	ACTUAL FAULT SET	SUCCESS
134	76A/63B	X3 = 1.06 X4 = 0.18	X4 = 0.20	YES
136	76A/62B	X2 = 1.59 X4 = 0.12	X4 = 0.15	YES
137	76A/53B	X1 = 1.49 X4 = 0.18	X2 = 1.56 X4 = 0.18	YES
138**	76A/63B	X3 = 1.06 X4 = 0.18	X4 = 0.18	YES
140	65A/54B	X4 = 0.30 X5 = 1.02	X4 = 0.30	YES
142	55A/54B	X1 = 1.55 X3 = 1.06	X4 = 0.33	NO
156	44A/38B	X1 = 1.45 X4 = 0.57	X1 = 1.48 X4 = 0.57	YES
153	34A/49B	X4 = 0.61 X5 = 1.02	X4 = 0.63	YES
155	34A/48B	X4 = 0.59 X5 = 1.02	X4 = 0.57	YES
157	45A/57B	X2 = 1.54 X4 = 0.53	X4 = 0.52	YES
158	54A/18B	X1 - 1.39 X2 = 0.52	X1 - 1.39	NO
159	45A/56B	X4 = 0.46 X5 = 0.98	X4 = 0.48	YES
164	55A/56B	X1 = 1.51 X3 = 1.10	X4 = 0.43	NO
165	25A/84B	X1 = 1.70 X2 = 1.66	X1 = 1.75 X4 = 0.43	PARTIAL
167***	35A/74B	X1 = 1.68 X2 = 1.60	X1 = 1.68 X4 = 0.40	YES

**See Test #134

*** See Test #82

TEST #	CELLS	DETERMINED FAULT SET	ACTUAL FAULT SET	SUCCESS
168****	55A/54B	X1 = 1.55 X3 = 1.06	X4 = 0.34	NO
169*****	45A/74B	X1 = 1.65 X5 = 1.01	X1 = 1.62 X4 = 0.34	PARTIAL
171	75A/16B	X1 = 1.38 X2 = 1.55	X1 = 1.34 X4 = 0.34	PARTIAL
203	57A/49B	X2 = 1.40 X3 = 1.32	X2 = 1.40 X3 = 1.28	YES
205	44A/95B	X2 = 1.74 X3 = 1.13	X2 = 1.68 X3 = 1.14	YES
206	54A/63B	X2 = 1.68 X3 = 0.95	X2 = 1.70 X3 = 0.99	YES
208	56A/87B	X2 = 1.54 X3 = 1.22	X2 = 1.56 X3 = 1.24	YES
209	57A/48B	X2 = 1.41 X3 = 1.30	X2 = 1.42 X3 = 1.24	YES
210	57A/18B	X1 = 1.35 X5 = 0.86	X2 = 1.35 X3 = 1.24	NO
212	54A/11B	X2 = 1.58 X3 = 0.93	X3 = 0.89 X4 = 0.45	PARTIAL
216	66A/64B	X2 = 1.54 X4 = 0.31	X3 = 1.11 X4 = 0.27	YES
217	35A/79B	X3 = 1.21 X4 = 0.56	X3 = 1.15 X4 = 0.55	YES
221	62A/88B	X3 = 1.40 X5 = 1.22	X3 = 1.32 X5 = 1.20	YES

****See Test #142

*****See Test #107

V. CONCLUSIONS AND DISCUSSION OF RESULTS

A. CONCLUSIONS

The method of multifault isolation presented in this paper is a workable procedure for isolating faults in linear networks. The degree of success attained in problem two represents a realistic starting point for achieving high success rates in relatively complex networks. Inspection of the data for problem two revealed that of the 10 failures, 5 were associated with tests in which the network had failed at only one frequency. In problem one, 4 of the 16 failures occurred when the network had failed at only one frequency. This indicates that if one is to detect very small drift failures, then the cells may have to be very small near the nominal values.

The success rates mentioned for joint signature were for a single solution to a set of equations. No multiple solutions were obtained but the lack of multiple solutions was not considered an important deficiency. No claim is made as to the distribution of the simulated network faults.

B. ADVANTAGES OF THE METHOD OF JOINT SIGNATURE

The foremost advantage of the isolation procedure by joint signature is its simplicity of application. Although it may take considerable effort to establish the joint signatures and to code particular cells to a fault set, this is required only once for any network. The fault diagnoser need only take and plot simple measurements. The network troubleshooter need have little knowledge of circuit theory or even of the particular circuit being tested. When equations of magnitude have been

utilized the equipment required may only be a signal generator and a volt meter. The procedure is general and may be applied to any linear network with possible applications to nonlinear systems.

C. A QUESTION OF FEASIBILITY

The problems encountered in solving simultaneous nonlinear equations and the large execution times required for complex networks may not allow the approach to be feasible. Certainly the procedure, because of the effort required to generate joint signatures, is limited to circuits which have wide use. One method to reduce problem complexity is to express the network function in terms of some comprehensive parameters rather than elements. The best isolation that could be obtained would then be to some group of elements or subnetwork. Utilizing the conventional two-port parameters would require a prohibitive number of variables (8 real) to describe a subnetwork assuming cascade two-port connections. Furthermore, if the parameters are not frequency independent then one is required to somehow obtain several network equations at one frequency.

The simple networks studied each had only one break frequency and so the choice of test frequencies was obvious. In complicated networks one will be required to take at least one measurement near each break frequency. This may also serve to determine the number of faults which will be considered.

If the network output is either zero or infinite one cannot apply the method of joint signature without utilizing interior test points. Otherwise, the magnitude of faults which can be considered is unlimited. It is expected that catastrophic failures are more easily isolated and thus the cell size might be increased farther away from nominal value. Further improvement in results could perhaps be obtained from using an improved procedure for selecting the fault pair. As mentioned, the method used depended on the logarithmic sensitivities being of the same order of magnitude. However, the sensitivities of elements one, two and three in problem four were 10^4 times those of elements four and five revealing why element four faults were difficult to isolate.

VI. SUGGESTIONS

A. EXTENSION TO COMPLEX LINEAR NETWORKS

Several questions concerning the feasibility of fault isolation by joint signature have already been posed. In order to arrive at some answers it is suggested that the joint signature concept be studied for three and four element faults in very simple networks. Since the number of possible cell combinations is $M(M-1)(M-2) \ldots (M-Q)$, where M is the number of cells at any frequency and Q is the number of measurements, large cells will be required with possibly smaller cells toward nominal values. However, as one increases the number of faults considered, the number of possible fault sets decreases. If one could consider N faults in a network of N elements, there would be only one fault set. Methods of expressing a network function in terms of some few parameters and of obtaining network measurements to determine faulty parameters are needed. Two possible approaches are to load the network with a variable known load or to utilize interior test points to measure intermediate network functions in the same parameters. The study should also allow for the detection of more than K faults.

B. APPLICATION TO NONLINEAR NETWORKS

Simple nonlinear networks may be studied to determine fault set selection techniques and applicability.

```
C       THIS IS A FORTRAN IV G PROGRAM TO SOLVE UP TO THREE SIMULTANEOUS      0010
C       COMPLEX EQUATIONS FOR UP TO SIX REAL VARIABLES.                       0020
C                                                                             0030
C                                                                             0040
C       THE PROGRAM LAYOUT IS DESIGNED FOR CIRCUIT ANALYSIS. THE              0050
C       EQUATIONS ARE THE TRANSFER FUNCTIONS OF A LINEAR CIRCUIT AT           0060
C       DIFFERENT FREQUENCIES.                                                0070
C       THE EQUATIONS (REAL) ARE NON-LINEAR AND IN THE SIMPLEST CASE          0080
C       ARE BIQUADRATIC. THIS PROGRAM ALLOWS THE DETERMINATION OF M           0090
C       ELEMENT VALUES (REAL UNKNOWNS) GIVEN M/2 COMPLEX EQUATIONS.           0100
C                                                                             0110
C       THE USER SUPPLIES ONE SUBROUTINE, SUBROUTINE CALCT, AND IN            0120
C       ADDITION FURNISHES THE DATA DECK.                                     0130
C                                                                             0140
CCC                                                                           0150
C                                                                             0160
C       DATA FORMAT IS DESCRIBED SEPARATELY                                   0170
        INTEGER P,PP,PA,PN                                                    0180
        COMPLEX S,T,CENT,Z,TNOM,SENX,SAVT                                     0190
        DIMENSION ERRMUG(200),DELV(50),DXNORM(50),DELXN(6)                    0200
        DIMENSION XVAR(6),EPO(20)                                             0210
        COMMON/ARRAY1/S(3),T(3),X(50)                                         0220
        COMMON/ARRAY2/CENT(15,15,3),TNOM(3)                                   0230
        COMMON/ARRAY3/PSAV(50)                                                0240
        COMMON/ARRAY4/SENX(50)                                                0250
        COMMON/ARRAY5/NVAR(6)                                                 0260
        COMMON/ARRAY6/Z(3)                                                    0270
        COMMON/ARRAY7/DELX(50)                                                0280
        COMMON/ARRAY8/XSAV(50),SAVT(3)                                        0290
C                                                                             0300
C       SUBROUTINE READ READS IN ALL DATA EXCEPT PERMUTATIONS                 0310
C                                                                             0320
        CALL READ(ICELL,IXLIM,IYLIM,NEQ,IMENT,NPERM,IVX,FSENS,ACC)            0330
C       TMUG IS THE SUM OF THE MAGNITUDES OF THE NOMINAL TRANSFER FUNCTIONS   0340
        TMUG=0.0                                                              0350
C       IPO IS AN INDICATOR TO SUBROUTINE PERM THAT PERMUTATION DATA          0360
C       IS TO BE READ.                                                        0370
        IPO=0                                                                 0380
C       CALCULATE TMUG                                                        0390
C       NEQ, INPUT DATA, IS THE # OF EQUATIONS.                               0400
        DO 17 IQ=1,NEQ                                                        0410
C       SUBROUTINE CALCT CALCULATES A VALUE OF THE TRANSFER FUNCTION          0420
C       USING CURRENT ELEMENT VALUES AND THE FREQUENCY IN THE S ARRAY         0430
C       DENOTED BY THE CALLING ARGUEMENT.                                     0440
        CALL CALCT(IQ)                                                        0450
C       THE TNOM ARRAY WILL RETAIN THE NOMINAL TRANSFER FUNCTIONS             0460
C       AT THE DIFFERENT FREQUENCIES.                                         0470
        TNOM(IQ)=T(IQ)                                                        0480
```

```
      TMUG=TMUG+CABS(TNOM(IQ))                                          0490
   17 CONTINUE                                                          0500
C     SUBROUTINE SENSIT CALCULATES THE SENSITIVITY FUNCTIONS OF ALL THE 0510
C     ELEMENTS OF THE TRANSFER FUNCTION.                                0520
C     IMENT, INPUT DATA, IS THE # OF ELEMENTS IN T(S).                  0530
C     FSENS IS THE FREQ AT WHICH SENSITIVITIES ARE CALCULATED AND       0540
C     IS PART OF THE DATA INPUT.                                        0550
      CALL SENSIT(FSENS,IMENT)                                          0560
      WRITE(6,111)                                                      0570
  111 FORMAT('1',20X,'SENSTIVITY FUNCTIONS CALCULATED AT S=J')          0580
      WRITE(6,112)FSENS                                                 0590
  112 FORMAT('+',59X,1F6.0,////)                                        0600
      DO 113 LU=1,IMENT                                                 0610
      WRITE(6,114)                                                      0620
  114 FORMAT('0',20X,'SENSITIVITY OF X(  )=')                           0630
      WRITE(6,115)LU,SENX(LU)                                           0640
  115 FORMAT('+',37X,1I2,2X,2E11.3)                                     0650
  113 CONTINUE                                                          0660
C     ACC IS THE REQUIRED ACCURACY ON SOLUTIONS AND IS FURNISHED DATA.  0670
C     ACC,AS USER SUPPLIED, IS A FRACTION OF TMUG. IN THE PROGRAM       0680
C     IT IS CONVERTED TO A REAL NUMBER.                                 0690
      WRITE(6,219)ACC                                                   0700
  219 FORMAT('0',20X,'ACCURACY LIMIT ON SOLUTION IS ',1E14.6)           0710
C     SUBROUTINE CENTER CALCULATES THE TRANSFER FUNCTION AT THE CENTER  0720
C     OF THE CELLS OF INTEREST.                                         0730
C     ICELL, INPUT DATA, IS THE CELL SIZE AS A PERCENTAGE OF TMUG.      0740
C     IXLIM, INPUT DATA, IS THE LIMIT ON THE REAL PART OF T(S) TO BE    0750
C     CONSIDERED. EXPRESSED AS A PERCENTAGE OF TMUG.                    0760
C     IYLIM IS A LIMIT ON THE IMAGINARY PART.                           0770
C     IF AND IG ARE DO LOOP LIMITS CALCULATED IN SUBROUTINE CENTER      0780
C     BASED ON ICELL,IYLIM,IXLIM.                                       0790
      CALL CENTER(ICELL,IXLIM,IYLIM,NEQ,IF,IG)                          0800
C     INITIALIZE ERRORS TO ZERO                                         0810
      ERRM=0.0                                                          0820
      ERMM=0.0                                                          0830
C     CONVERT ACC TO PURE NUMBER                                        0840
      ACC=(ACC*TMUG)                                                    0850
C     NOW BEGIN THE MINIZATION PROCESS, THE STARTING POINT DEPENDS ON THE 0860
C     NUMBER OF EQUATIONS NEQ                                           0870
      IF(NEQ.EQ.1)GO TO 71                                              0880
      IF(NEQ.EQ.2)GO TO 72                                              0890
C     THE DO LOOPS GOING TO 18 DETERMINE THE VALUES OF T(S), UP TO 3,   0900
C     OF INTEREST WHICH ARE STORED IN THE CENT ARRAY.THE FIRST DIMENSION 0910
C     OF CENT GIVES THE REAL CELL NUMBER, THE 2ND GIVES THE IMAGINARY,  0920
C     THE 3 RD THE FREQUENCY TO BE USED.                                0930
      DO 21 IR=1,IF                                                     0940
      DO 21 IS=1,IG                                                     0950
C     Z(3) IS THE CURRENT VALUE OF T(S) AT THE 3RD FREQUENCY            0960
```

```
      Z(3)=CENT(IR,IS,3)                                                    0970
C     S(3) IS THE 3RD FREQUENCY , IN COMPLEX FORM                           0980
      F3=AIMAG(S(3))                                                        0990
C     THE ERROR OR OBJECTIVE FUNCTION IS THE MAGNITUDE OF THE               1000
C     DIFFERENCE OF THE REQUIRED VALUE OF T(S) AND THE CURRENT VALUE        1010
C     OF T(S) CALCULATED FROM CURRENT ELEMENT VALUES.                       1020
C     THE REQUIRED VALUES OF T(S) ARE IN THE CENT ARRAY AND ARE             1030
C     TRANSFERED TO THE Z ARRAY.                                            1040
      ERMM=((CABS(Z(3)-TNOM(3)))                                            1050
 72   DO 22 J5=1,IF                                                        1060
      DO 22 J6=1,IG                                                         1070
      Z(2)=CENT(J5,J6,2)                                                    1080
      ERRM=(CABS(Z(2)-TNOM(2)))                                             1090
      F2=AIMAG(S(2))                                                        1100
 71   DO 18 J7=1,IF                                                        1110
      DO 18 J8=1,IG                                                         1120
      Z(1)=CENT(J7,J8,1)                                                    1130
C     THE ERRMUG ARRAY CONTAINS THE VALUES OF THE OBJECTIVE FUNCTIONS       1140
C     ON SUCCESSIVE ITERATIONS. OBJ FUNCTION AND ERROR TERM WILL BE USED    1150
C       INTERCHANGEABLY.                                                    1160
C     THE 1ST ERROR TERM IS THE SUM OF THE MAGNITUDES OF                    1170
C     THE DIFFERENCE FROM NOMINAL T(S)'S AND DESIRED VALUES OF T(S)         1180
      ERRMUG(1)=ERRM+ERMM+(CABS(Z(1)-TNOM(1)))                              1190
      F1=AIMAG(S(1))                                                        1200
      WRITE(6,116)                                                          1210
 116  FORMAT('1',25X,'////////////////////////////////////////////////////   1220
     C////////////////////////////////')                                     1230
      WRITE(6,117)                                                          1240
      WRITE(6,117)                                                          1250
 117  FORMAT(' ',25X,'/                                                    1260
     C                                /')                                  1270
      IF(NEQ.EQ.3)WRITE(6,121)                                              1280
 121  FORMAT(' ',25X,'/     CELL #',9X,'FREQUENCY=',10X,'RPS',7X,'CENTER    1290
     C=',25X,'/')                                                          1300
      IF(NEQ.EQ.3)WRITE(6,122)IR,IS,F3,Z(3)                                 1310
 122  FORMAT('+',37X,1I2,1X,1I2,14X,1F9.2,18X,1F7.4,3X,1F7.4)               1320
      IF(NEQ.EQ.2)WRITE(6,121)                                              1330
      IF(NEQ.GE.2)WRITE(6,122)J5,J6,F2,Z(2)                                 1340
      WRITE(6,121)                                                          1350
      WRITE(6,122)J7,J8,F1,Z(1)                                             1360
      WRITE(6,117)                                                          1370
      WRITE(6,117)                                                          1380
      WRITE(6,131)                                                          1390
 131  FORMAT(' ',25X,'////////////////////////////////////////////////////   1400
     C////////////////////////////////')                                     1410
      WRITE(6,301)                                                          1420
 301  FORMAT('0',/)                                                         1430
C     SUBROUTINE PERM SELECTS A WORKING SET OF VARIABLES, TWICE THE         1440
```

```
C       NUMBER OF EQUATIONS, FROM THE POSSIBLE  VARIABLES, THESE                1450
C       ARE FURNISHED DATA.                                                     1460
C       NPERM IS THE NUMBER OF PERMUTATIONS.                                    1470
        DO 20 JB=1,NPERM                                                        1480
        CALL PERM(IVX,JB,NPERM,IPO)                                             1490
C       MUM IS AN INDICATOR TO LIMIT THE NUMBER OF ITERATIONS                   1500
        MUM=1                                                                   1510
        IFG=1                                                                   1520
        ERRSAV=ERRMUG(MUM)                                                      1530
        IF((J8.NE.IG/2+1).OR.(J7.NE.IF/2+1)) GO TO 63                           1540
        IF(NEQ.EQ.1) GO TO 61                                                   1550
        IF((J6.NE.J8).OR.(J5.NE.J7)) GO TO 63                                   1560
        IF(NEQ.EQ.2)GO TO 61                                                    1570
        IF((IS.NE.J8).OR.(IR.NE.J7)) GO TO 63                                   1580
        GO TO 61                                                                1590
 63     NUM=1                                                                   1600
        DX=0.05                                                                 1610
C       DX DETERMINES THE STEP SIZE FROM LOCAL MINIMUM                          1620
C       SIGN DETERMINES THE DIRECTION OF STEP IN CONJUNCTION WITH PN            1630
C       PP, AND PA.                                                             1640
        SIGN=-1.0                                                               1650
        PN=1                                                                    1660
        PP=0                                                                    1670
        PA=0                                                                    1680
        C=1.0                                                                   1690
        ISTEP=2                                                                 1700
C       RSAV ARRAY SAVES NOMINAL VALUES                                         1710
C       XSAV ARRAY SAVES BEST ESTIMATES THUS FAR                                1720
        DO 171 LAN=1,IVX                                                        1730
        NAN=NVAR(LAN)                                                           1740
 171    XSAV(LAN)=RSAV(LAN)                                                     1750
   33   CONTINUE                                                                1760
        MAM=MUM                                                                 1770
        MUM=MUM+1                                                               1780
        ERRMUG(MUM)=0.0                                                         1790
C       ERRMAG IS AN INTERIM ERROR VALUE AT ONLY ONE FREQUENCY                  1800
C       IFIG IS A COUNTER FOR DE-INCREMENTING.                                  1810
        IFIG=1                                                                  1820
        IF(MUM.GE.200)GO TO 49                                                  1830
C       DSUM IS CURRENT VALUE OF OBJECTIVE FUNCTION                             1840
        DSUM=ERRMUG(MAM)                                                        1850
C       NEWRAP PERFORMS MODIFIED NEWTON-RAPHSON METOD ON VARIABLES              1860
        CALL NEWRAP(NEQ,DSUM,IVX,ACC,C)                                         1870
C       CALCULATE NEW ERROR TERM USING NEW ESTIMATES.                           1880
 211    DO 19 IT=1,NEQ                                                          1890
        CALL CALCT(IT)                                                          1900
        ERRMUG(MUM)=ERRMUG(MUM)+CABS(T(IT)-Z(IT))                               1910
 19     CONTINUE                                                                1920
```

```
C       IS ERROR LESS THAN REQUIRED ACCURACY ?                                  1930
C       IF SO WRITE ANSWERS                                                     1940
 87     IF(ERRMUG(MUM).LE.ACC)GO TO 25                                          1950
C       IBACK IS AN INDICATOR THAT DE-INCREMENTING IS REQUIRED.                 1960
        IBACK=2                                                                 1970
        IF(MUM.GT.10)ICOUNT=MUM-10                                              1980
C       NEXT CARD DETECTS A BLOW UP.                                            1990
        IF((ERRMUG(MUM).GT.ERRMUG(1)).AND.(MUM.GT.10))GO TO 69                  2000
C       INCREMENT WAS TOO LARGE. DE-INCREMENT.                                  2010
 504    IF(ERRMUG(MUM).GT.ERRMUG(MAM)) IBACK=1                                  2020
 245    IF(ERRMUG(MUM).GT.ERRMUG(MAM)) GO TO 54                                 2030
        IF(MUM.LE.10)GO TO 611                                                  2040
C       TEST RATE OF MINIZATION TO DETECT A LOCAL MINIMA.                       2050
        IF(((ERRMUG(ICOUNT)-ERRMUG(MUM)).LT.0.05*ERRMUG(ICOUNT)))GO TO 69       2060
C       MINIZATION TAKING PLACE, SAVE GOOD ESTIMATES                            2070
 611    ERRSAV=ERRMUG(MUM)                                                      2080
        DO 141 JUN=1,IVX                                                        2090
        KUN=NVAR(JUN)                                                           2100
 141    XSAV(KUN)=X(KUN)                                                        2110
        DO 161 LUN=1,NEQ                                                        2120
 161    SAVT(LUN)=T(LUN)                                                        2130
        GO TO 33                                                                2140
 61     DO 62 MUNG=1,NEQ                                                        2150
 62     T(MUNG)=TNOM(MUNG)                                                      2160
C       STATEMENTS 25 TO 66 PRINT OUT ANSWERS OR BEST ESTIMATES                 2170
 25     DO 40 IJK=1,IVX                                                         2180
        ILK=NVAR(IJK)                                                           2190
        DELV(ILK)=X(ILK)-RSAV(ILK)                                              2200
        DXNORM(ILK)=DELV(ILK)*CABS(SENX(ILK))                                   2210
        DELXN(IJK)=DXNORM(ILK)                                                  2220
        XVAR(IJK)=X(ILK)                                                        2230
 40     CONTINUE                                                                2240
        SOLN=1.0                                                                2250
        DO 59 K2=1,NEQ                                                          2260
        WRITE(6,43)                                                             2270
 43     FORMAT('0 ','MUM=',9X ,'DELXN(   )=',16X,'X(   )=',18X,'T(   )=',23X,  2280
     C'ERROR=')                                                                 2290
        WRITE(6,42)MUM,NVAR(K2),DELXN(K2),NVAR(K2),XVAR(K2),K2,T(K2),ERRMU      2300
     CG(MUM)                                                                    2310
 42     FORMAT('+',5X,1I4,11X,1I2,2X,1E11.3,7X,1I2,2X,1E11.3,9X,1I2,2X,1F7      2320
     C.3,3X,1F7.3,12X,1E11.3)                                                   2330
 59     CONTINUE                                                                2340
        NAQ=NEQ+1                                                               2350
        DO 66 K9=NAQ,IVX                                                        2360
        WRITE(6,67)                                                             2370
 67     FORMAT('0',        14X ,'DELXN(   )=',16X,'X(   )=')                    2380
        WRITE(6,68) NVAR(K9),DELXN(K9),NVAR(K9),XVAR(K9)                        2390
 68     FORMAT('+',20X,1I2,2X,1E11.3,7X,1I2,2X,1E11.3)                          2400
```

```
 66    CONTINUE                                                          2410
       WRITE(6,301)                                                      2420
       IF(ISTEP.EQ.1)GO TO 70                                            2430
       GO TO 32                                                          2440
C      SUBROUTINE TWOVAR PERFORMS RELAXATION METHOD ON VARIABLES         2450
C      WHEN NEWTON-RAPHSON METHOD FAILS.                                 2460
 49    CALL TWOVAR(ACC,SOLN,IVX,NEQ,ERROR)                               2470
       ERRMUG(MUM)=ERROR                                                 2480
       IF(SOLN.EQ.2)GO TO 25                                             2490
       IF(ERROR.LE.(10.0*ACC)) GO TO 39                                  2500
       GO TO 32                                                          2510
C      LAST INCREMENT WAS TOO LARGE, SUBTRACT PART OFF. CONTINUE THIS    2520
C      PROCESS UNTIL ERROR INCREASES.                                    2530
 54    ERD(IFIG)=ERRMUG(MUM)                                             2540
C      ERD ARRAY IS TEMP STORAGE FOR ERROR TERMS WHILE DE-INCREMENTING.  2550
  798  IFM=IFIG                                                          2560
       IFIG=IFIG+1                                                       2570
C      IF ERROR HAS INCREASED, ADD BACK LAST INC AND EXIT.               2580
C      LIMIT IS 20 DE-INCREMENTS.                                        2590
 613   IF(IFIG.GE.20)GO TO 33                                            2600
       DO 616 KUNE=1,IVX                                                 2610
       P=NVAR(KUNE)                                                      2620
 616   X(P)=X(P)-.40*DELX(P)                                             2630
       IFIG=IFIG+1                                                       2640
C      AFTER DE-INCREMENTING GO TO 79 AND CALC NEW ERROR TERM.           2650
   79  ERD(IFIG)=0.0                                                     2660
       DO 624 MAN=1,NEQ                                                  2670
       CALL CALCT(MAN)                                                   2680
 624   ERD(IFIG)=ERD(IFIG)+CABS(Z(MAN)-T(MAN))                           2690
       IF(ERD(IFIG).LT.ERD(IFM)) GO TO 798                               2700
 752   DO 751 LAG=1,IVX                                                  2710
       P=NVAR(LAG)                                                       2720
 751   X(P)=X(P)+.40*DELX(P)                                             2730
       ERRMUG(MUM)=ERD(IFM)                                              2740
       DO 614 LULU=1,NEQ                                                 2750
 614   CALL CALCT(LULU)                                                  2760
C      END OF DE-INCREMENTING ROUTINE.                                   2770
       GO TO 33                                                          2780
 39    WRITE(6,118)                                                      2790
 118   FORMAT('0        NO SOLUTION GENERATED. THE FOLLOWING VALUES ARE  2800
      CTHE BEST ESTIMATES')                                              2810
C      ERRMUG(MUM)=ERRSAV                                                2820
       DO 151 MUN=1,IVX                                                  2830
       NUN=NVAR(MUN)                                                     2840
  151  X(NUN)=XSAV(NUN)                                                  2850
       DO 800 JYZ=1,NEQ                                                  2860
 800   T(JYZ)=SAVT(JYZ)                                                  2870
       GO TO 25                                                          2880
```

```
C       STATEMENTS 69 TO 81 STEP THE FUNCTION OUT OF A LOCAL MINIMUM          2890
C       IN VARIOUS DIRECTIONS, DEPENDING ON THE NUMBER OF THE TRY, AND        2900
C       ALSO GIVE A NEW STARTING POINT TO A SEARCH THAT HAS BLOWN UP.         2910
C       THE MAGNITUDE OF THE STEP IS INCREASED EACH TIME A NEW STEP           2920
C       IS TAKEN IN A PREVIOUSLY TRIED DIRECTION.                             2930
 69     NOM=NOM+1                                                             2940
        SOLN=1.0                                                              2950
        IF((NOM.EQ.2).OR.(NOM.EQ.3).OR.(NOM.EQ.4)) GO TO 53                   2960
        DXMAG=DX*FLOAT(PN)                                                    2970
        PP=PP+1                                                               2980
        PA=PA+1                                                               2990
        IF(PP.NE.IVX+1)GO TO 70                                               3000
        SIGN=SIGN*(-1.0)                                                      3010
        PP=1                                                                  3020
        ISTEP=1                                                               3030
C       IF(ERRMUG(MUM).LT.(((FLOAT(ICELL))*TMUG)/200.0)) GO TO 39             3040
 70     P=NVAR(PP)                                                            3050
        IFG=IFG+1                                                             3060
        ISTEP=2                                                               3070
        IF(IFG.GT.20) GO TO 49                                                3080
        IF(PA.EQ.(2*IVX))PN=PN+1                                              3090
        IF(PA.EQ.(2*IVX))PA=0                                                 3100
        X(P)=RSAV(P)*(1.0+DXMAG*SIGN)                                         3110
        ERRMUG(MUM)=0.                                                        3120
        DO 81 KOW=1,NEQ                                                       3130
        CALL CALCT(KOW)                                                       3140
        ERRMUG(MUM)=ERRMUG(MUM)+(CABS(T(KOW)-Z(KOW)))                         3150
   81   CONTINUE                                                              3160
        IF(ERRMUG(MUM).GT.ERRMUG(1))GO TO 69                                  3170
        IM=MUM-1                                                              3180
        DO 89 ISN=ICOUNT,IM                                                   3190
   89   ERRMUG(ISN)=ERRMUG(MUM)*1.05                                          3200
        GO TO 33                                                              3210
 53     C=C/3.0                                                               3220
        DO 55 KIN=1,IVX                                                       3230
        LIN=NVAR(KIN)                                                         3240
 55     X(LIN)=RSAV(LIN)                                                      3250
CC      MAYBE NEED TO USE RSAV                                                3260
        DO 56 MIN=1,NEQ                                                       3270
 56     T(MIN)=TNOM(MIN)                                                      3280
CC      OR TNOM(MIN)                                                          3290
        ERRMUG(MUM)=ERRSAV                                                    3300
        GO TO 33                                                              3310
C       AFTER EACH SEARCH RESTORE VARIABLES TO THEIR NOMINAL VALUES           3320
 32     DO 31 MM=1,IMENT                                                      3330
        X(MM)=RSAV(MM)                                                        3340
 31     CONTINUE                                                              3350
 20     CONTINUE                                                              3360
```

```
   21 CONTINUE                                                          3370
      IF(NEQ.EQ.1)STOP                                                  3380
   22 CONTINUE                                                          3390
      IF(NEQ.EQ.2)STOP                                                  3400
   18 CONTINUE                                                          3410
      STOP                                                              3420
      END                                                               3430



      SUBROUTINE NEWRAP(NEQ,DSUM,IVX,ACC,C)                             3480
      INTEGER P                                                         3490
      COMPLEX S,T,TSAV,Z                                                3500
      DIMENSION TSAV(3),DF(2),D2F(6),DX(6),D1F(6)                       3510
      COMMON/ARRAY1/S(3),T(3),X(50)                                     3520
      COMMON/ARRAY3/RSAV(50)                                            3530
      COMMON/ARRAY5/NVAR(6)                                             3540
      COMMON/ARRAY6/Z(3)                                                3550
      COMMON/ARRAY7/DELX(50)                                            3560
C     NVAR ARRAY CONTAINS SUBSCRIPTS OF CURRENT VARIABLES               3570
C     SELECT, SEQUENTIALLY, THE VARIABLE TO BE INCREMENTED,SUBSCRIPT P  3580
C     SAVE CURRENT TRANSFER FUNCTIONS VALUES                            3590
      DO 7 IJ=1,NEQ                                                     3600
      TSAV(IJ)=T(IJ)                                                    3610
    7 CONTINUE                                                          3620
C     CALC 1ST AND 2ND DERIVATIVES OF X(P)                              3630
      DO 29 L=1,IVX                                                     3640
      P=NVAR(L)                                                         3650
      DX(L)=1.E-2*RSAV(P)                                               3660
      IF(DSUM.LT.10.0*ACC)DX(L)=0.01*DX(L)                              3670
    8 DO 101 M2=1,2                                                     3680
      DELTAF=0.0                                                        3690
      X(P)=X(P)+DX(L)                                                   3700
      DO 99 M1=1,NEQ                                                    3710
      CALL CALCT(M1)                                                    3720
      DELTAF=DELTAF+(CABS(T(M1)-Z(M1)))                                 3730
   99 CONTINUE                                                          3740
      IF(M2.EQ.1)SAVE=DELTAF                                            3750
      IF(M2.EQ.1)DF(1)=DELTAF-DSUM                                      3760
      IF(M2.EQ.2)DF(2)=DELTAF-SAVE                                      3770
  101 CONTINUE                                                          3780
C     IF 2ND DER IS ZERO AVOID DIVIDE CHECK ERROR                       3790
      IF(ABS(DF(2)-DF(1)).LE.1.E-9)DX(L)=DX(L)*10.0                     3800
      IF(ABS(DF(2)-DF(1)).LE.1.E-9)GO TO 8                              3810
   79 D2F(L)=(DF(2)-DF(1))/DX(L)**2                                     3820
```

```
 83   D1F(L)=(DF(1)+DF(2))/(2.0*DX(L))                                  3830
      FACT=1./C                                                         3840
C     NEAR SOLUTION LIMIT INCREMENT STEPS.                              3850
      IF(DSUM.LE.10.0*ACC)FACT=0.5/C                                    3860
C     CALCULATE INCREMENT BY NEWTON-RAPHSON                             3870
      DELX(P)=(-D1F(L)/D2F(L))*FACT                                     3880
C     LIMIT DELTA X(P) TO 0.2*(MAG OF X(P))                             3890
      IF(ABS(DELX(P)).GT.(0.1*ABS(X(P))))DELX(P)=0.1*DELX(P)*ABS(X(P)/DE 3900
     CLX(P))                                                            3910
      X(P)=X(P)-2.0*DX(L)                                               3920
 2C   CONTINUE                                                          3930
      DO 31 N=1,IVX                                                     3940
      P=NVAR(N)                                                         3950
 31   X(P)=X(P)+DELX(P)                                                 3960
      DO 61 K4=1,NEQ                                                    3970
      T(K4)=TSAV(K4)                                                    3980
 61   CONTINUE                                                          3990
      RETURN                                                            4000
      END                                                               4010
```



```
      SUBROUTINE READ(ICELL,IXLIM,IYLIM,NEQ,IMENT,NPERM,IVX,FSENS,ACC)  4060
      COMPLEX S,T                                                       4070
      DIMENSION FREQS(3)                                                4080
      COMMON/ARRAY1/S(3),T(3),X(50)                                     4090
      COMMON/ARRAY3/RSAV(50)                                            4100
      READ(5,1)ICELL,IXLIM,IYLIM,NEQ,IMENT,NPERM,FSENS,ACC              4110
 1    FORMAT(6I10,/,2F10.0)                                             4120
      IVX=2*NEQ                                                         4130
      READ(5,2) (X(IA),IA=1,IMENT)                                      4140
 2    FORMAT(1F20.0)                                                    4150
      READ(5,2) (FREQS(IB),IB=1,NEQ)                                    4160
      DO 3 IC=1,NEQ                                                     4170
      S(IC)=CMPLX(0.0,FREQS(IC))                                        4180
 3    CONTINUE                                                          4190
      DO 8 IK=1,IMENT                                                   4200
      RSAV(IK)=X(IK)                                                    4210
 8    CONTINUE                                                          4220
      RETURN                                                            4230
      END                                                               4240
```

```
C      THIS SUBROUTINE IS USER SUPPLIED. ONLY THE TRANSFER                    4290
C      FUNCTION EXPRESSION T(N) IS CHANGED.                                   4300

       SUBROUTINE CALCT(N)                                                    4310
       COMPLEX S,T                                                            4320
       COMMON/ARRAY1/S(3),T(3),X(50)                                          4330
       T(N)=X(5)/(X(1)*X(2)*X(3)*X(4)*X(5)*S(N)**4+X(1)*X(2)*X(3)*S(N)**3     4340
     C+(X(3)*X(4)*X(5)+X(1)*X(4)*X(5)+X(1)*X(2)*X(5))*S(N)**2+(X(3)+X(1)      4350
     C)*S(N)+X(5))                                                          4360
       RETURN                                                                 4370
       END                                                                    4380



       SUBROUTINE PERM(IVX,JB,NPERM,IPO)                                      4430
       DIMENSION NV(50,6)                                                     4440
       COMMON/ARRAY5/NVAR(6)                                                  4450
       IPO=IPO+1                                                              4460
       IF(IPO.EQ.1)GO TO 5                                                    4470
       GO TO 6                                                                4480
 5     DO 21 K=1,NPERM                                                        4490
       READ(5,4) (NVAR(JU),JU=1,IVX)                                          4500
       DO 21 M=1,IVX                                                          4510
       NV(K,M)=NVAR(M)                                                        4520
  21   CONTINUE                                                               4530
 6     DO 7 L=1,IVX                                                           4540
 7     NVAR(L)=NV(JB,L)                                                       4550
    4  FORMAT(5I2)                                                            4560
       RETURN                                                                 4570
       END                                                                    4580



       SUBROUTINE CENTER(ICELL,IXLIM,IYLIM,NEQ,IF,IG)                         4630
       COMPLEX CENT,TNOM                                                      4640
       DIMENSION ANOM(3),RNOM(3),TMUG(3)                                      4650
       COMMON/ARRAY2/CENT(15,15,3),TNOM(3)                                    4660
       ID=IXLIM/ICELL                                                         4670
       IE=IYLIM/ICELL                                                         4680
       IF=2*ID+1                                                              4690
       IG=2*IE+1                                                              4700
```

```
      CELL=FLOAT(ICELL)/100.                                              4710
      DO 6 N=1,NEQ                                                        4720
      ANOM(N)=AIMAG(TNOM(N))                                              4730
      RNOM(N)=REAL(TNOM(N))                                               4740
      TMUG(N)=CABS(TNOM(N))                                               4750
      DO 6 IH=1,IF                                                        4760
      A1=FLOAT(IH)                                                        4770
      A2=FLOAT(IXLIM)/100.0 +CELL                                         4780
      Y1=A1*CELL*TMUG(N)+RNOM(N)-A2*TMUG(N)                               4790
      DO 6 II=1,IG                                                        4800
      A4=FLOAT(II)                                                        4810
      A5=FLOAT(IYLIM)/100.0+CELL                                          4820
      Z1=A4*CELL*TMUG(N)+ANOM(N)-A5*TMUG(N)                               4830
      CENT(IH,II,N)=CMPLX(Y1,Z1)                                          4840
6     CONTINUE                                                            4850
      RETURN                                                              4860
      END                                                                 4870
```



```
      SUBROUTINE SENSIT(FSENS,IMENT)                                      4920
      COMPLEX SSAV,SENX,S,DELTAT,T1,T,CDX                                 4930
      COMMON/ARRAY1/S(3),T(3),X(50)                                       4940
      COMMON/ARRAY3/RSAV(50)                                              4950
      COMMON/ARRAY4/SENX(50)                                              4960
      SSAV=S(1)                                                           4970
      S(1)=CMPLX(0.0,FSENS)                                               4980
      CALL CALCT(1)                                                       4990
      T1=T(1)                                                             5000
      DO 16 IP=1,IMENT                                                    5010
      DX=1.E-4*RSAV(IP)                                                   5020
      X(IP)=X(IP)+DX                                                      5030
      CDX=CMPLX(0.0,DX)                                                   5040
      CALL CALCT(1)                                                       5050
      DELTAT=T(1)-T1                                                      5060
      SENX(IP)=DELTAT/CDX                                                 5070
      X(IP)=X(IP)-DX                                                      5080
16    CONTINUE                                                            5090
      S(1)=SSAV                                                           5100
      T(1)=T1                                                             5110
      RETURN                                                              5120
      END                                                                 5130
```

```
      SUBROUTINE TWOVAR(ACC,SOLN,IVX,NEQ,ERROR)                          5180
      COMPLEX T,SAVT,Z,S                                                 5190
      INTEGER P                                                          5200
      DIMENSION B(50),ERRMUG(500)                                        5210
      COMMON/ARRAY1/S(3),T(3),X(50)                                      5220
      COMMON/ARRAY3/RSAV(50)                                             5230
      COMMON/ARRAY5/NVAR(6)                                              5240
      COMMON/ARRAY6/Z(3)                                                 5250
      COMMON/ARRAY8/XSAV(50),SAVT(3)                                     5260
      DO 1 K=1,IVX                                                       5270
      L=NVAR(K)                                                          5280
      B(L)=0.1                                                           5290
C     MAY WANT TO START AT NOMINAL INSTEAD                               5300
 1    X(L)=XSAV(L)                                                       5310
      ERRMUG(1)=0.0                                                      5320
      DO 2 M=1,NEQ                                                       5330
      CALL CALCT(M)                                                      5340
 2    ERRMUG(1)=ERRMUG(1)+CABS(T(M)-Z(M))                                5350
      ERRSAV=ERRMUG(1)                                                   5360
      MUM=1                                                              5370
C     FOLLOWING IS INITIAL CHOICE OF VARIABLE TO BE INCREMENTED          5380
      MM=1                                                               5390
      P=NVAR(MM)                                                         5400
 216  F=0.1                                                              5410
 201  LUM=1                                                              5420
 215  ICOUNT=1                                                           5430
 203  DO 3 N=1,IVX                                                       5440
      KA=NVAR(N)                                                         5450
 3    X(KA)=X(KA)-F*RSAV(KA)                                             5460
      MUM=MUM+1                                                          5470
      ICO=ICOUNT                                                         5480
      ICOUNT=ICOUNT+1                                                    5490
      ERRMUG(ICOUNT)=0.0                                                 5500
      DO 4 KB=1,NEQ                                                      5510
      CALL CALCT(KB)                                                     5520
 4    ERRMUG(ICOUNT)=ERRMUG(ICOUNT)+ CABS(T(KB)-Z(KB))                   5530
      IF(ERRMUG(ICOUNT).GE.ERRMUG(ICO)) GO TO 202                        5540
      ERRSAV=ERRMUG(ICOUNT)                                              5550
      DO 5 KC=1,IVX                                                      5560
      KD=NVAR(KC)                                                        5570
 5    XSAV(KD)=X(KD)                                                     5580
      DO 6 KE=1,NEQ                                                      5590
 6    SAVT(KE)=T(KE)                                                     5600
      IF(ERRMUG(ICOUNT).LE.ACC)GO TO 10                                  5610
      GO TO 203                                                          5620
```

```
202   DO 7 KF=1,IVX                                                    5630
      KG=NVAR(KF)                                                      5640
7     X(KG)=X(KG)+F*RSAV(KG)                                           5650
      IF(ICOUNT.NE.2)GO TO 12                                          5660
      ICOUNT=1                                                         5670
204   ICO=ICOUNT                                                       5680
      ICOUNT=ICOUNT+1                                                  5690
      DO 8 KH=1,IVX                                                    5700
      KI=NVAR(KH)                                                      5710
8     X(KI)=X(KI)+F*RSAV(KI)                                           5720
      MUM=MUM+1                                                        5730
      ERRMUG(ICOUNT)=0.0                                               5740
      DO 9 KJ=1,NEQ                                                    5750
      CALL CALCT(KJ)                                                   5760
9     ERRMUG(ICOUNT)=ERRMUG(ICOUNT)+CABS(T(KJ)-Z(KJ))                  5770
      IF(ERRMUG(ICOUNT).GE.ERRMUG(ICO)) GO TO 205                      5780
      ERRSAV=ERRMUG(ICOUNT)                                            5790
      DO 20 KK=1,IVX                                                   5800
      KL=NVAR(KK)                                                      5810
20    XSAV(KL)=X(KL)                                                   5820
      DO 71 KM=1,NEQ                                                   5830
71    SAVT(KM)=T(KM)                                                   5840
      IF(ERRMUG(ICOUNT).LE.ACC) GO TO 10                               5850
      GO TO 204                                                        5860
205   DO 82 KN=1,IVX                                                   5870
      KO=NVAR(KN)                                                      5880
82    X(KO)=X(KO)-F*RSAV(KO)                                           5890
      IF(ICOUNT.NE.2) GO TO 12                                         5900
      ICOUNT=1                                                         5910
206   ICO=ICOUNT                                                       5920
      ICOUNT=ICOUNT+1                                                  5930
      DO 81 KP=1,IVX,2                                                 5940
      KQ=NVAR(KP)                                                      5950
81    X(KQ)=X(KQ)+F*RSAV(KQ)                                           5960
      DO  83 KR=2,IVX,2                                                5970
      KS=NVAR(KR)                                                      5980
83    X(KS)=X(KS)-F*RSAV(KS)                                           5990
      MUM=MUM+1                                                        6000
      ERRMUG(ICOUNT)=0.0                                               6010
      DO 84 KT=1,NEQ                                                   6020
      CALL CALCT(KT)                                                   6030
84    ERRMUG(ICOUNT)=ERRMUG(ICOUNT)+CABS(T(KT)-Z(KT))                  6040
      IF(ERRMUG(ICOUNT).GE.ERRMUG(ICO)) GO TO 207                      6050
      ERRSAV=ERRMUG(ICOUNT)                                            6060
      DO 85 KU=1,IVX                                                   6070
      KW=NVAR(KU)                                                      6080
85    XSAV(KW)=X(KW)                                                   6090
      DO 86 KX=1,NEQ                                                   6100
```

```
86    SAVT(KX)=T(KX)                                                          6110
      IF(ERRMUG(ICOUNT).LE.ACC)GO TO 10                                       6120
      GO TO 206                                                               6130
207   DO 87 KY=1,IVX,2                                                        6140
      KZ=NVAR(KY)                                                             6150
87    X(KZ)=X(KZ)-F*RSAV(KZ)                                                  6160
      DO 88 LA=2,IVX,2                                                        6170
      LB=NVAR(LA)                                                             6180
88    X(LB)=X(LB)+F*RSAV(LB)                                                  6190
      IF(ICOUNT.NE.2) GO TO 12                                                6200
      ICOUNT=1                                                                6210
208   ICO=ICOUNT                                                              6220
      ICOUNT=ICOUNT+1                                                         6230
      MUM=MUM+1                                                               6240
      DO 60 LC=1,IVX,2                                                        6250
      LD=NVAR(LC)                                                             6260
60    X(LD)=X(LD)-F*RSAV(LD)                                                  6270
      DO 61 LE=2,IVX,2                                                        6280
      LF=NVAR(LE)                                                             6290
61    X(LF)=X(LF)+F*RSAV(LF)                                                  6300
      ERRMUG(ICOUNT)=0.0                                                      6310
      DO 62 LF=1,NEQ                                                          6320
      CALL CALCT(LF)                                                          6330
62    ERRMUG(ICOUNT)=ERRMUG(ICOUNT)+CABS(T(LF)-Z(LF))                         6340
      IF(ERRMUG(ICOUNT).GE.ERRMUG(ICO)) GO TO 209                             6350
      ERRSAV=ERRMUG(ICOUNT)                                                   6360
      DO 63 LG=1,IVX                                                          6370
      LH=NVAR(LG)                                                             6380
63    XSAV(LH)=X(LH)                                                          6390
      DO 64 LI=1,NEQ                                                          6400
64    SAVT(LI)=T(LI)                                                          6410
      IF(ERRMUG(ICOUNT).LE.ACC) GO TO 10                                      6420
      GO TO 208                                                               6430
 209  DO 66 LJ=1,IVX,2                                                        6440
      LK=NVAR(LJ)                                                             6450
66    X(LK)=X(LK)+F*RSAV(LK)                                                  6460
      DO 67 LL=2,IVX,2                                                        6470
      LM=NVAR(LL)                                                             6480
67    X(LM)=X(LM)-F*RSAV(LM)                                                  6490
      IF(ICOUNT.NE.2) GO TO 12                                                6500
      IF(F.LE.1.0E-5) GO TO 12                                                6510
      F=F/10.0                                                                6520
      GO TO 215                                                               6530
15    ICOUNT=1                                                                6540
11    X(P)=X(P)+B(P)*RSAV(P)                                                  6550
      ICO=ICOUNT                                                              6560
      ICOUNT=ICOUNT+1                                                         6570
      IF(LUM.GE.50)GO TO 214                                                  6580
```

```
      LUM=LUM+1                                                          6590
      MUM=MUM+1                                                          6600
      IF(ICOUNT.EQ.20) GO TO 124                                         6610
      IF(ICOUNT.EQ.50) GO TO 214                                         6620
119   IF(MUM.GE.200)GO TO 19                                             6630
      ERRMUG(ICOUNT)=0.0                                                 6640
      DO 401 LN=1,NEQ                                                    6650
      CALL CALCT(LN)                                                     6660
401   ERRMUG(ICOUNT)=ERRMUG(ICOUNT)+CABS(T(LN)-Z(LN))                    6670
      IF(ERRMUG(ICOUNT).GE.ERRMUG(ICO)) GO TO 99                         6680
      ERRSAV=ERRMUG(ICOUNT)                                              6690
      XSAV(P)=X(P)                                                       6700
      DO 403 LQ=1,NEQ                                                    6710
403   SAVT(LQ)=T(LQ)                                                     6720
      IF(ERRMUG(ICOUNT).LE.ACC)GO TO 10                                  6730
      GO TO 11                                                           6740
99    X(P)=X(P)-B(P)*RSAV(P)                                             6750
      IF(ICOUNT.NE.2)GO TO 12                                            6760
89    ICOUNT=1                                                           6770
16    X(P)=X(P)-B(P)*RSAV(P)                                             6780
      ICO=ICOUNT                                                         6790
      ICOUNT=ICOUNT+1                                                    6800
      LUM=LUM+1                                                          6810
      IF(LUM.GE.50) GO TO 214                                            6820
      MUM=MUM+1                                                          6830
      IF(ICOUNT.EQ.20)GO TO 125                                          6840
      IF(ICOUNT.GE.50) GO TO 214                                         6850
117   IF(MUM.GE.200) GO TO 19                                            6860
      ERRMUG(ICOUNT)=0.0                                                 6870
      DO 404 LR=1,NEQ                                                    6880
      CALL CALCT(LR)                                                     6890
404   ERRMUG(ICOUNT)=ERRMUG(ICOUNT)+CABS(T(LR)-Z(LR))                    6900
      IF(ERRMUG(ICOUNT).GE.ERRMUG(ICO)) GO TO 13                         6910
      ERRSAV=ERRMUG(ICOUNT)                                              6920
      XSAV(P)=X(P)                                                       6930
      DO 406 LU=1,NEQ                                                    6940
406   SAVT(LU)=T(LU)                                                     6950
      IF(ERRMUG(ICOUNT).LE.ACC) GO TO 10                                 6960
      GO TO 16                                                           6970
13    X(P)=X(P)+B(P)*RSAV(P)                                             6980
      GO TO 12                                                           6990
214   ERRMUG(1)=ERRMUG(ICO)                                              7000
      GO TO 201                                                          7010
124   B(P)=B(P)*15.0                                                     7020
      GO TO 119                                                          7030
125   B(P)=B(P)*15.0                                                     7040
      GO TO 117                                                          7050
19    SOLN=1.0                                                           7060
```

```
      EPROR=ERRSAV                                                      7070
      RETURN                                                            7080
 12   ERRMUG(1)=ERRMUG(ICO)                                             7090
      IF(ICOUNT.EQ.2)GO TO 65                                           7100
      MM=MM+1                                                           7110
      IF(MM.EQ.IVX+1)MM=1                                               7120
      P=NVAR(MM)                                                        7130
      GO TO 15                                                          7140
 65   B(P)=B(P)/5.0                                                     7150
      GO TO 15                                                          7160
 10   SULN=2.0                                                          7170
      ERROR=ERRMUG(ICOUNT)                                              7180
      RETURN                                                            7190
      END                                                               7200
                                                                        7210
                                                                        7220
                                                                        7230
                                                                        7240
C     SAMPLE DATA DECK FOLLOWS.  DATA IS FOR SAMPLE PROBLEM TWO.        7250
         5         20         20          1          5         10      7260
1.          0.001                                                       7270
1.5307                                                                  7280
1.5772                                                                  7290
1.0824                                                                  7300
0.3824                                                                  7310
1.                                                                      7320
1.2                                                                     7330
 1  2                                                                   7340
 1  3                                                                   7350
 1  4                                                                   7360
 1  5                                                                   7370
 2  3                                                                   7380
 2  4                                                                   7390
 2  5                                                                   7400
 3  4                                                                   7410
 3  5                                                                   7420
 4  5                                                                   7430
```

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13. ABSTRACT

A study was made to isolate one and two component faults in simple linear networks by the method of joint signature of order two whereby two measurements of a failed network are coded to all possible combinations of two component values which will produce that fault with all other elements at nominal values. Two additional measurements were obtained, a new joint signature of order two generated, and the faulty component set was selected as the fault pair with the same values at both joint signatures. The method involves numerous solutions of sets of nonlinear equations. By assuming many values of a failed network function the equations were presolved on a one time only basis for a network. One and two component faults were simulated in two simple low pass filter networks. The highest success rate in isolating faults was approximately 80%.

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